

a b c Types of Inverted Folds (Heim, Mechanismus der Gebirgsbildung)



Fig. 1 Symmetrical Fold



Fig 2 Overfold Type a



Fig 3 Overfold Type b

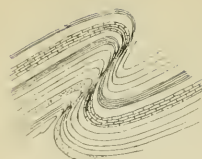


Fig 4 Overfold Type c.

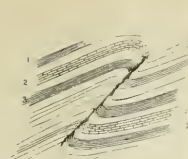


Fig 5 Overfault

Type of Denuded Mountain System
Section through North portion of Central Alps
Heim, Mechanismus der Gebirgsbildung, Taf. XII fig. 13

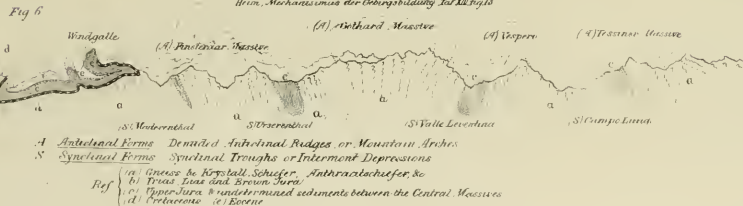


Fig 6

Type of Symmetrical Mountain Ridge, &c.

(Geological Section of the Mont Blanc Range
(M. Favre, Recherches Géologiques, 1867, Pl. VIII Fig. 1)

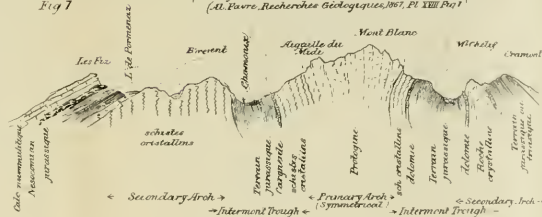


Fig 7

Geological Section from the Baumgarten-Alp to the Fucha horn (Heun, op. cit. Taf VII Prof. XII)

Showing deceptive arrangement of Strata in the flank of a denuded Niangua Range.



Fig 8'

*Eroded & Compressed Intermont Trough
Strata on both sides inverted
(Favre Recherches Géologiques, Plate V fig 27)*



Fig. 9

Reference to Fig 10

Development of planes of dislocation in a stratum subjected to lateral pressure.

(a) *Direction of lateral pressure*

(b) Direction of local yielding of lamina.

(c) Confluent lines of dislocation

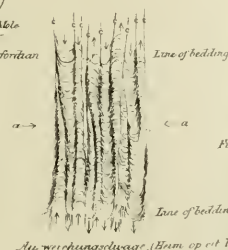


Fig. 10

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ORIGINAL ARTICLES.

I.—THE SECRET OF THE HIGHLANDS.

By Prof. CHARLES LAPWORTH, F.G.S.

(PLATE VIII.)

(Continued from p. 199.)

(b). *Special Principles of Mountain Structure, etc.*

Heim's theory of inclined folds (overfolds).

THE theory of the gradual formation of overfolds and overfaults in a stratified system is thus developed by Professor Heim:¹—

Wherever a stratified rock series is subjected to the lateral horizontal thrust of the earth's crust, a *fold* is originated. This fold consists of two opposed and symmetrical members, with more or less remote axes, viz. (Plate VIII. Fig. 1)

(1) An upward bend, or *arch*; and

(2) A similar downward bend, or *trough*, parallel to the former.

Connecting this arch and this trough lies a zone forming a *common* or *middle limb*.

(a) As the crushing continues, the arch *rises*, the trough *sinks*, and the middle limb *revolves* as a relatively neutral intermediate portion, and gradually attains a perpendicular attitude. As the pressure still increases, the middle limb is even forced somewhat beyond the vertical, and becomes inverted in position. In this way the trough-curve is brought *below* the arch-curve, and there originates first an *overhanging*, and finally an inclined fold (Plate VIII. Fig. 2).

During this process the lateral pressure has squeezed thinner those strata of different materials which are inclosed together in the central parts of the fold, while those in the main curves have been rendered somewhat thicker; but all three limbs of the fold have experienced the effects of the pressure in a similar measure.

If the compressing force has been neutralized at this stage, we obtain in this way an inclined fold, whose arch, middle limb, and trough limb are formed of about equal strength.

(b) In the case (a) described above, if the middle limb is very short, so that its double breadth has become wholly insufficient to withstand the amount of the compressing force—that is to say, if the pressure is more than sufficient to overturn the middle limb, the mechanical arrangement becomes considerably altered.

¹ Heim, Mechanismus der Gebirgsbildung, Band I. pp. 220–223.

The arch-limb, which has given way in an upward direction to the lateral pressure upon the strata, now overlaps *above*, while the trough-limb thrusts itself *downwards* below in the diametrically opposite direction. Both arch-limb and trough-limb suffer from the general horizontal side-thrust of the earth-crust *only*; but the intermediate middle limb lies wedged in between two masses of strata moving in opposite directions, at the same time that it is enormously burdened by the weight of the superimposed arch-limb and arch-core, while, in addition, it is squeezed by a component of the general side-thrust. As a natural result, the middle limb suffers a mechanical action, which may most fitly be termed a *mangling* or *rolling-out-action*, and must thereby become *longer*.

As the strata enveloped in the fold gradually give way to the lateral compressing forces, the beds forming the arch-limb can only move forward at the crest of the fold (which has a sharp curvature), by rolling themselves over in a downward direction towards the squeezed middle limb. There constantly takes place, therefore, an over-rolling movement at the *crest*, as the folding goes on. Having, in this manner, arrived in the region of the middle limb, the various strata formerly belonging to the arch-limb are there crushed and rolled out.

A corresponding and symmetrical movement takes place in the *trough-curve*. The end of the trough-curve is dragged upward in a rolling movement towards the middle limb, where its strata are crushed, flattened out, and extended.

On the *convex* or outside parts of the arch and trough-curves there is a continual tendency of the particles to the constantly lengthening middle-limb: on the *concave* or inside parts of these curves there is a corresponding movement from the centre of the middle limb towards the apices of the curves. The geologically *younger beds* of the folding system (*i.e.* the parts within the arch and trough-axes) move *downwards below* the under side of the middle limb; the geologically *older beds* glide *upwards* above the upper side of the middle limb. But these changes of position of the particles can never proceed, however, so quickly as the advancing movement of the over-riding and underthrust masses, for they have merely been rolled and dragged along by the latter.

Through the rolling-out process described above, the mass of strata dragged over the arch-bend grows thinner and thinner the greater its distance becomes from the overturning brow of the arch. In the same way, the lower portion of the middle limb, which feeds itself from the trough-limb by dragging particles upwards, rolls out thinner and thinner the farther it becomes removed from the trough-bend. Between both these regions the precise spot where the middle limb is at its weakest marks the special point where, in the original formation of the inclined fold, the curve between arch and trough originally changed direction, and which has therefore experienced for the longest time the rolling and dragging-out action in both directions.

(As a general rule the middle limb is rolled out uniformly, but

this is not invariably the case. It is sometimes torn into individual shreds, between which the strata of the arch-core and those belonging to the trough-core touch each other.)

Whilst in the first type (*a*) of inclined fold described, a piece of strata corresponding with the width between the trough-limb and the arch-limb, is predestined from the very beginning to be the later middle-limb of the inclined fold; in this second type (*b*), the middle limb originates in great measure by the gradual curving round and rolling out of pieces of the two side-limbs. During the infancy of the fold (*b*), the particles eventually composing the middle limb were mostly portions of the lateral limbs, and underwent a mechanical transformation in their gradual transition into the middle-limb. It is evident that the zones of strata which were thus *dragged* by the two side-limbs into the central limb have, when combined, a collective breadth necessarily much inferior to that of the middle limb which has been *rolled out* of this material.

In the first case (*a*) the original breadth of the compressed zone of earth-crust enveloped in the final fold corresponded to the sum total of the *three* limbs; but in the second case (*b*), it only corresponds to the sum of the *two* side-limbs, plus a fraction of the middle limb.

(Although the process described above may be regarded as the normal mode of origin of the second type of inclined fold, it may nevertheless be developed very naturally out of the fold of the first type, if the compressing force be more than sufficient for the formation of (*a*).)

(*c*) As a third member in the series, there is the case when the middle limb is no longer sufficiently fed by the lateral limbs, or when the folding and rolling out go too far, or are continued to such an extent that the movements taking place in opposite directions on both sides of the middle limb, as well as the opposite movements of arch portion (limb and core), and trough portion (limb and core), are of necessity compelled to concentrate themselves upon an intermediate layer of middle-limb of ever-diminishing thickness. Finally, they come of necessity into immediate contact, and when this takes place, the arch-portion and trough-portion of the overfold are *completely sheared off from each other*. Instead of the middle limb we have now a surface of dislocation; and *the arch portion of the fold thrusts itself over the trough portion in the form of a more or less rigid mass*.

In many cases this overthrusting effect is due to the relief of downward pressure caused by the erosion of the brow of the arch. As a general rule, the trough bend is much longer able to furnish fresh material to the central limb than the arch bend, so that we find many inclined folds, which in their trough portions are of the type (*b*), and in their arch portions of the type (*c*). In these folds, a central limb is still recognizable in the vicinity of the trough bend, but, in the vicinity of the overlapping crest, they have become a rigid overthrust mass, without a trace of central limb.

We find consequently among inclined or reflexed folds a connected

series of forms, each successive member of which may arise naturally from the preceding merely by an increase in the force of compression. These overfolds may be thus distinguished :—

(a) An overfold, originating by the overthrow of a central limb previously limited by two differently directed curves has three limbs of about equal strength.

(b) An overfold with gradual development of a middle limb, which has originated in the over-rolling of the beds at the apices of the curves, has a greatly reduced middle limb.

(c) The overfold which has originated by the shearing off of the arch portion from the trough portion, and upthrust of the former over the latter, has either (*c*¹) a middle limb squeezed very thin or else (*c*²) no middle limb at all. We find in this last type the two following cases :—

(*c*³.) The arch portion of the middle limb is missing, but the trough portion is still present.

(*c*⁴.) The entire middle limb is wanting.

The arch limb and trough limb of an overfold merely undergo side-thrust ; the middle limb suffers *stretching, rolling out, and squeezing*. The deeper they lie below the surface the greater is the ductility of the strata. In overfolds of vast extent the arch limb being nearer the surface is more rigid, the trough limb, being buried under more than double the burden, is more ductile. It often breaks up therefore under compression into a complete series of secondary folds. The position of these minor folds is prescribed to them by the limits of the primary trough of the overfold, for the whole space is filled up, and yielding is only possible in those directions in which the whole mass gives way. From this results the frequent harmonic folding of the trough limb.

Such is the theory of the gradual development of reflexed folds as laid down by Heim in his great work ; and no one who has carefully studied in detail the appearances of the strata enveloped in the numberless overfolds in convoluted rocks, can possibly doubt its general correctness. Accepting, therefore, this fundamental theory as it stands, we obtain the following additional principles of mountain structure :—

11. In the process of the folding of the beds in an overfold (Plate VIII. Figs. 1—5), while the particles in the roof and floor of the overfold become crushed more closely together, those in the middle limb are subjected to gradually increasing extension. This gives in orderly sequence the successive formation of

- (1) An overfold composed of three nearly equal limbs.
- (2) An overfold with insignificant middle limb.
- (3) An overfold with local relics of a middle limb.
- (4) An overfold with a plane of dislocation in lieu of the middle limb (*fold-fault*).
- (5) As the pressure increases, the strata shear along the plane of dislocation ; the axial plane of the fold (plexal axis) becomes the plane of an inverted fault, and the arch portion of the fold slides upwards over the trough portion until equilibrium is restored (*upthrust*).

In all the last three cases the final results are almost identical. The roof and floor of the overfold (arch-limb and trough-limb) repose at once upon each other apparently in regular and conformable succession.

12. By a series of repeated folds and faults of this nature, a rock formation of no great actual thickness lying upon the flanks of an ancient mountain range may be made to crop out over an enormous area, presenting the fallacious appearance of a massive formation of immense thickness, but of a most monotonous petrological character, being apparently formed of alternations of similar strata, which follow each other in parallel and unbroken order. Or, on the other hand, if the strata in this position include those of several distinct but conformable geological formations, these same physical accidents will necessarily give to the whole mass the fallacious appearance of a single and consecutive rock-series, whose strata all agree generally in dip, strike, and amount of convolution (Plate VIII. Fig. 8).

13. As a final result, however, in a theoretically symmetrical mountain range, if all disturbing elements are eliminated, broad parallel zones of such strata should flank the mountain range on both sides, as we approach the mountain axis. The corresponding zones on opposite flanks should be formed of identical strata, and answer precisely to each other in amount of convolution and average inclination. The crest of the range being longest exposed to denudation should show an axial zone of the oldest rocks, the youngest should occur in the plains at the foot. In other words, the folding, the faulting, and the geological age of the strata should all decrease in exact proportion as we pass outward from the vertical strata along the mountain axis through the plagioclinic rocks of its flanks, to the orthoclinic beds of the fringing plains.

The foregoing are perhaps the main principles which bear upon the appearances presented by comparatively homogeneous strata looped up by opposed parallel pressures into symmetrical folds of infinite length, perpendicular to the plane of curvature. But in actual mountain regions, none of these conditions obtain over a large area. The rock-formations implicated are very different in lithological characters, and vary greatly in their relative resistance to deformation under pressure. The tangential thrust differs much in local intensity, while the major loops are in truth long and irregular domes. Hence within a convoluted region all these phenomena must vary locally both in form and degree, and may be arrested at any stage, or, in the process of time (by the development of new and differently applied pressures), may be supposed to be extended indefinitely.

But before treating of the special modifications of the foregoing results which take place in nature, there are two additional conclusions which appear to flow so naturally from the application of the foregoing principles that they must be noticed in this connection.

Deformation of Individual Strata.

14. In all those cases hitherto considered, the masses of strata

undergoing deformation lie near the surface, and, owing to the absence of overlying rocks, they have comparative freedom of movement in a vertical direction. They consequently yield to the tangential crust stress by looping themselves up in *broad masses* into vast arches, the crests of which are directed obliquely outwards perpendicularly to the direction of local thrust; and the phenomena we have described affect the *entire mass of strata* enveloped in each fold, *considered as a whole*.

But at great depths beneath the surface, where the strata are overburdened by masses of superimposed rocks (and also in the cores and curves of the larger arches and folds themselves, where they are surrounded by enveloping rock-masses), the deforming strata have no longer the same freedom of vertical movement. Hence we may infer as a natural result, that the amplitude of the rock folds grows less and less in proportion as the weight of overlying material increases. The various stages of rock deformation under lateral pressure (folds, overfolds, overfaults, and overthrusts), under these new conditions are theoretically of the same *kind* as before, and take place in the same *sequence*, but are of rapidly diminishing *degree*.

As a typical term in the descending series, we select that theoretical case in which we shall suppose that the tangential thrust acts upon one stratum only.

As the general rock-mass in which it is imbedded gives way as a whole to the grand horizontal stress, the stratum is wrinkled up into a series of corrugations, the magnitude of which depend upon (a) the weight of the overlying rocks, (b) the thickness of the stratum itself, and (c) its comparative hardness and density.

As the overlying mass gives way and rises above each individual bed becomes in this way crumpled inwards upon itself into a set of minute and more or less symmetrical folds, each of which consists as before of an upward curve or arch, and a downward curve or trough, and an intermediate neutral wall or common limb, the axial planes of all three being approximately parallel, and inclined in that special direction in which the general mass of strata is giving way. As the process goes on, each bed may retain its individuality, but must of necessity become greatly increased in apparent thickness, viz. to an extent which is measured by the amplitude of its folds.

As the pressure increases, the several stages of rock-deformation already described here follow each other in their natural sequence. The miniature normal folds pass into overfolds with attenuated middle limb; next into overfolds with insignificant or fragmentary common wall, till finally the latter may become obliterated altogether and become replaced by a plane of dislocation, the roof and floor of each miniature overfold resting at once upon each other in regular and conformable sequence.

During this process those parts of the stratum forming the two side limbs have undergone compression and condensation: those in the neighbourhood of the common wall have been submitted to twisting and elongation. In all the later stages of its deformation, therefore, the bed is made up of wedges of strengthened material,

whose thickened extremities are turned in opposite directions, and these wedges are separated from each other by planes of weakness, or of actual dislocation.

It is needless perhaps to follow this process farther. It is clear that in all its later stages the bed will be found to have undergone a peculiar change in its dimensions, having been greatly compressed in one direction, and elongated in another. It has given way under the lateral thrust by wrinkling itself up into folds whose axes are perpendicular to the direction of local pressure; and the entire mass is finally traversed by a series of planes of structural weakness (fold-faults) coincident with the axes of these contortions. In other words, we have before us simply the gradual development of that special type of schistosity, which is correctly identified by Sorby in his classical paper¹ with true slaty cleavage.

From the conditions of the case all the phenomena of corrugation must be attended with great local irregularities, and may be more or less incapable of being referred to their proper type. But the various stages of the process of deformation ought fairly to be identified by the gradual disappearance of the miniature arch and trough-curves, and the final obliteration of the middle wall, *and its replacement by a plane of cleavage*. Some of the stages appear to be illustrated in the published figures indicated below.² In the earlier stages the corrugation is easily recognizable as such. In the intermediate stages we seem to have that interesting appearance which has been interpreted as false contorted bedding. In some of the later stages we find the thickened stratum traversed by those oblique laminations, which are usually regarded as affording unequivocal evidences of the false-bedded nature of the metamorphic schists.

Deformation of mountain folds.

If the causes and results of overfolding of rocks under tangential thrust are correctly laid down in the preceding paragraphs, in so far as they affect the groups of strata involved in the *minor folds* upon the flanks of mountain chains, they must, theoretically, be equally true of the grander masses of strata enveloped in the *regional earth-waves*, each of which gives origin to a single chain in a mountain system (Plate VIII., Fig. 7). When these mighty arches and troughs are brought closer together by the great crust-creep, the arches must

¹ On the Origin of Slaty Cleavage, by H. C. Sorby, F.G.S., etc., Edinburgh New Philosophical Journal, July, 1853.

² Compare:—

(a) Corrugations only—*rugæ* continuous.

Ramsay, Geol. N. Wales, 1881, p. 239, fig. 96.

Geikie, Handbook Geology, 1882, p. 520, fig. 245.

(b) Corrugation with diminished middle wall.

Ramsay, *Ibid.* p. 231, figs. 78 and 79.

Geikie, *Ibid.* 120, fig. 19.

(c) Corrugation with dislocation planes ("contorted false bedding").

Geikie, *Ibid.* p. 479, fig. 189.

Lyell's Students' Elements, ed. 1871, fig. 628.

(d) *Overfolding and faulting* of *rugæ*.

(e) *Overthrust*, Bonney, Quart. Journ. Geol. Soc. 1883, pl. 39, fig. 2.

rise and the intermediate troughs must sink.¹ The great monoclinical folds defining the several mountain-flanks must gradually develop into magnificent overfolds, and these again in the process of time into overfaults, having the appearance of normal dislocations with tremendous vertical downthrow. Only, however, in ranges geologically new, or composed of rock-formations of immense thickness, can these features be expected to be typically developed. The reader may collect abundant illustrations of this structure from the magnificent maps and sections of the Uinta and Wasatch areas in Western America, where both these conditions appear to obtain; and may observe how this theory brings into harmony many of the known facts of the interrelations of the folding, faulting, and remarkable physical geography of that wonderful region, and reconciles at the same time some of the apparently diverse interpretations of its geological development put forward by its enthusiastic describers.

In more easily convoluted regions, or in mountain chains of much higher antiquity, this inevitable relation of sunken trough to mountain arch is necessarily less conspicuous, and long eludes detection owing to the bewildering complexities of the strata involved. But it is by no means impossible that the long straight (longitudinal or strike valleys) and so-called *anticlinal* valleys of the Scottish Highlands, such as those of the Great Glen and Loch Tay, walled in by steep hill-slopes and occupied by lakes of profound depth, are nothing more than greatly depressed intermont *synclinal troughs* owing their origin to the same causes which bring about the slow secular elevation and approximation of their flanking ranges.

II.—ON HYPERSTHENE ANDESITE.

By J. J. HARRIS TEALL, M.A., F.G.S.

AT the conclusion of my last paper on the Cheviot andesites and porphyrites (GEOL. MAG. Vol. X. p. 262), I called attention to the close resemblance between the Cheviot hypersthene andesite (or porphyrite) and a rock from Steinerne Mann, Nahe, which has been called a *proterobase*.² Both rocks are black in colour and consist

¹ To this relation of sunken trough and mountain arch, there can, indeed, be no exception. The grand arch constituting a mountain chain is most properly regarded as an elevated anticlinal limited exteriorly by two depressed synclinals. Hence the paragraph ix. (a) 4 (p. 198) is mechanically incorrect as it stands, and should read:—

(IX. 4.) At the foot of either bounding synclinal of a mountain range the thrust is wholly horizontal; the twisting or shearing force is zero or very small, and the resulting folds are normal (symmetrical) and regular. But as we proceed towards the centre of the anticlinal of the range, this horizontal thrust is combined with a vertical component due to the weight of the mass above; the total thrust therefore becomes greater, and, moreover, its direction is more or less oblique to the transverse section of the rock, *i.e.* the twisting or shearing force becomes greater also. (The maximum of these latter effects occurs somewhere near the junction of the syncline and the anticline.) As a natural consequence the axes of the folds no longer remain vertical, but slope obliquely outwards, in the manner of inclined or reflexed folds.

² The term *proterobase* was introduced by Gumbel (Die paläolithischen Eruptivgesteine des Fichtelgebirges, München, 1874) for certain rocks occurring in the